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The impact of battery storage technologies in residential buildings with sub-daily autonomy and EV contribution

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Abstract. This study has been undertaken to gain a better understanding regarding the choice and impact of battery storage technologies in a use case with contribution of an electric vehicle to the overall domestic consumption. The study assessed the storage requirements of nine battery technologies for different residential building scales at the distribution level considering sub-daily autonomy periods. The use case explored in this paper assumed that the battery from an electric vehicle could contribute to the overall domestic consumption during the required hours of storage based on a scenario addressing demand response through peak shifting in 2030 (DR 2030) from an earlier study. After deriving the nominal capacity for each battery technology, the spatial requirements, including footprint, volume and mass, as well as the cost, for the scales of interest were estimated. The study showed that space and cost savings of up to 90% compared to a use case that do not consider EV contribution could be achieved. The choice of the most suitable technology according to its applicability in different building scales and different use cases should be carefully assessed.

1. Introduction

Sustainability and the irreversible depletion of natural resources has been the subject of constant debate in a global scale. The building and construction sectors together are found to be in charge of 39% of energy-related CO₂ emissions [1]. In addition, buildings' final energy demand continued to increase over the past years, as energy efficiency efforts have not compensated for the rising floor area [1]. According to [2], a stronger encouragement and support for electric mobility, electric heating and electricity access could result in a 90% increase in energy demand from today to 2040. Identifying opportunities to reduce this demand has become a priority in the global effort to deal with climate change. In addition, a very ambitious target set by the EU entails a significant CO₂ reduction by 80 to 95% by 2050 compared to 1990 levels [3]. At the same time, expansion of the electricity generation from renewable energy sources is already at the forefront of energy planning and along with electrical energy storage, they are expected to play a key role in the future built environment [4], contributing to CO₂ reductions.

In this study, an investigation on the storage requirements for the different residential scales in the case that an electric vehicle (EV) makes a contribution by meeting part of the storage requirement. The aim of this study is to investigate the impact of battery storage technologies in residential buildings, which account for the biggest share among commercial, industrial, agriculture, public administration and transport sectors [5]. Aspects such as whether storage at home level would be required, what its



effective capacity would be and what range of space and cost savings would be achieved were explored. The investigation addressed battery integration at building or community scale in the UK, considering only high energy battery storage applications in grid-connected systems. The research work indicates what considerations architects would need to give to this subject in the design of buildings in the future, where electrical energy storage systems are likely to be part of the design [6]. As no models or tools have been found dealing specifically with the size and location of energy storage systems [7], this research work has partially addressed this shortcoming through the consideration of a framework, within which these issues are explored. The presented work could facilitate making informed design decisions with regard to energy storage systems in the medium term from the end-users' point of view.

2. Methodology

In this study nine battery technologies were investigated based on technology and energy consumption data for a demand response scenario through peak shifting in 2030 (DR 2030) presented in earlier studies [8-10]. The data, which inform the effective capacity of the battery, are derived in ranges, meaning that the lowest and highest consumption values correspond to low and high consumption households respectively. The study focuses on the final level of distribution in the UK and the number of electrically heated households supplied at this level was found to be 75 [11], which set the upper boundary of the community scale in this study. In order to specify the electricity storage requirements for the residential sector, three steps were followed, as outlined in [10]. First, the specification of the nominal capacity of the battery bank was calculated, then the technologies' applicability in the different scales was assessed and finally the specification of the technologies' spatial and cost requirements were estimated based on the nominal capacity values. For the values that appear in ranges, two separate sets of data and graphs were produced. Thus a low range and a high range were derived respectively, as indicated in the figures.

The houses were assumed to be grid-connected and powered by renewable energy technologies, namely solar PVs. The PVs were assumed to generate electricity during the day, so that surplus electricity is stored in a battery. The electricity stored in the battery is then discharged during the evening and/or night hours to power the needs of the house. The model presented in this study forces the battery to be emptied completely each night, as is suggested by [12].

2.1. Use cases

Two use cases were investigated in this study based on the DR 2030 scenario. Use case 1 considered the discharge of the residential battery from 5pm to 12am (7 hours of storage), as the evening peak load starts to occur at about 5pm and as [13] also suggest. Use case 2 builds on use case 1 and assumed that the battery from an EV could contribute to the overall domestic consumption during the required (7) hours of storage. This could be performed through the charging of an EV in a charging station away from the owner's home, but at a relative proximity. Assuming that the vehicle's battery holds a considerable amount of the capacity when arriving home, it could be used to power (part of) the electrical needs of the home in the evening. Although two use cases were investigated using the same methodology, only the results of use case 2 and a comparison with the general results of use case 1 are presented in this paper due to the limited suggested length of this paper.

Considering the overall daily electricity consumption for electrically heated households on a winter day in weekend (7.1-17 kWh, taken from Figure 7 in [9]) and its distribution over the day (taken from Figure 4 in [9]), the calculation of the consumption from 5pm-12am was made possible. It was assumed that the EV contribution would be in the range of its typical daily consumption, so that the discharge of the battery at home is similar to its recharge before arriving home. For this, an electricity consumption of 0.16 kWh/km [14] and a daily distance coverage of 37 km [15] were considered, which result in an EV contribution of 6 kWh for use case 2. While this is a relatively focused exploration, future studies including sensitivity analyses could provide a better understanding of different ways of EV contribution.

The load profile for an electrically heated household in DR 2030 scenario and the two use cases are presented in **Figure 1**. It is shown that for use case 2 only 1.3 kWh of effective storage capacity ($C_{eff/h}$)

is required as a maximum. As for the minimum value in this case, not only is no storage required, but also the EV could contribute another 2.9 kWh.

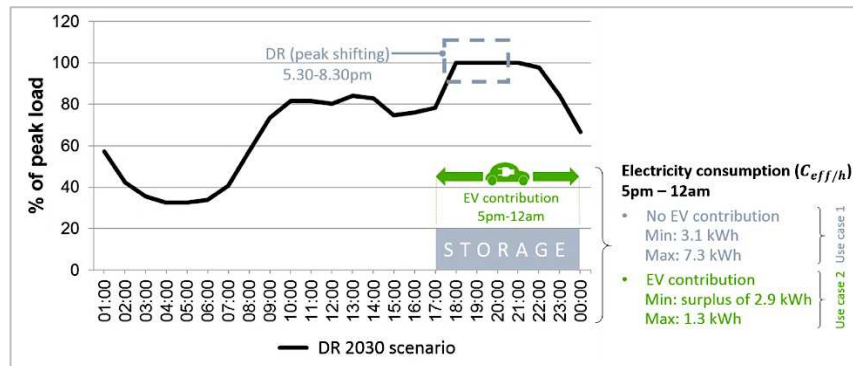


Figure 1. Load profile for an electrically heated household in DR 2030 and use cases 1 and 2

2.2. Electrical energy storage capacity for the nine battery technologies and their applicability at the different scales

The nominal capacity, applicability, footprint, volume, mass, investment cost and levelised cost of electricity (LCOE) were calculated or estimated following the methodology presented in [10], considering the following parameters: round-trip efficiency (η_{batt}), depth of discharge (DOD), temperature factor (k_t), aging factor (k_a), design margin (DM) and the inverter's efficiency (η_{inv}). The nominal capacity $C_{nom/h}$ for each of the technologies in the use cases described above was calculated using the equation below based on the effective capacity $C_{eff/h}$ from **Figure 1**:

$$C_{nom/h} = \frac{C_{eff/h} * k_t * k_a * DM}{\eta_{batt} * DOD * \eta_{inv}}$$

It was assumed that minimal self-discharge would occur during the hours of operation of the battery, so no self-discharge factor was considered. For the assessment of the batteries' applicability in different scales, the nominal capacity values were compared against the energy rating range for each battery technology found in [8]. Where the required nominal capacity value was outside the energy rating range, the technology was considered unsuitable for the respective scale.

2.3. Footprint, volume, mass, investment cost and levelised cost of electricity

The footprint, volume, mass, the investment cost and the LCOE for the nine battery technologies at different scales were derived, based on the nominal battery capacity values calculated in the previous section and the information included in Table 1 from [10]. For the values that appear in ranges, two separate sets of data and graphs are produced and presented in this section. Thus, through the consideration of the minimum and maximum values a low and a high range are derived respectively.

3. Results

As there is a linear correlation between the number of properties and the values regarding nominal battery capacity and spatial requirements, the results for up to 5 properties for use case 2 are displayed.

3.1. Electrical energy storage capacity for the nine battery technologies and their applicability at the different scales

An illustration of the battery technologies' nominal capacity values and their applicability or not to community scales up to 5 households for the use case studies is presented in **Figure 2**. In case of no applicability, the coloured blocks - which the columns consist of and which address minimum or maximum nominal capacity values - are void. Minimum and maximum nominal capacity correspond to low and high consumption households respectively.

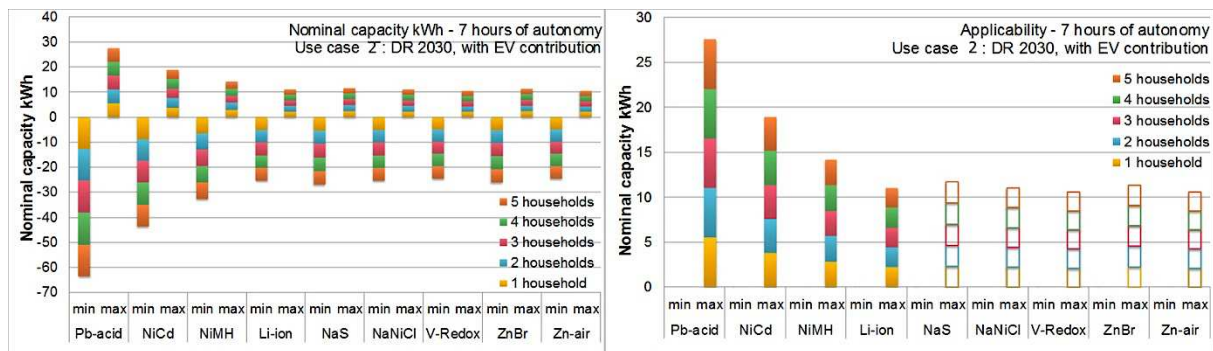


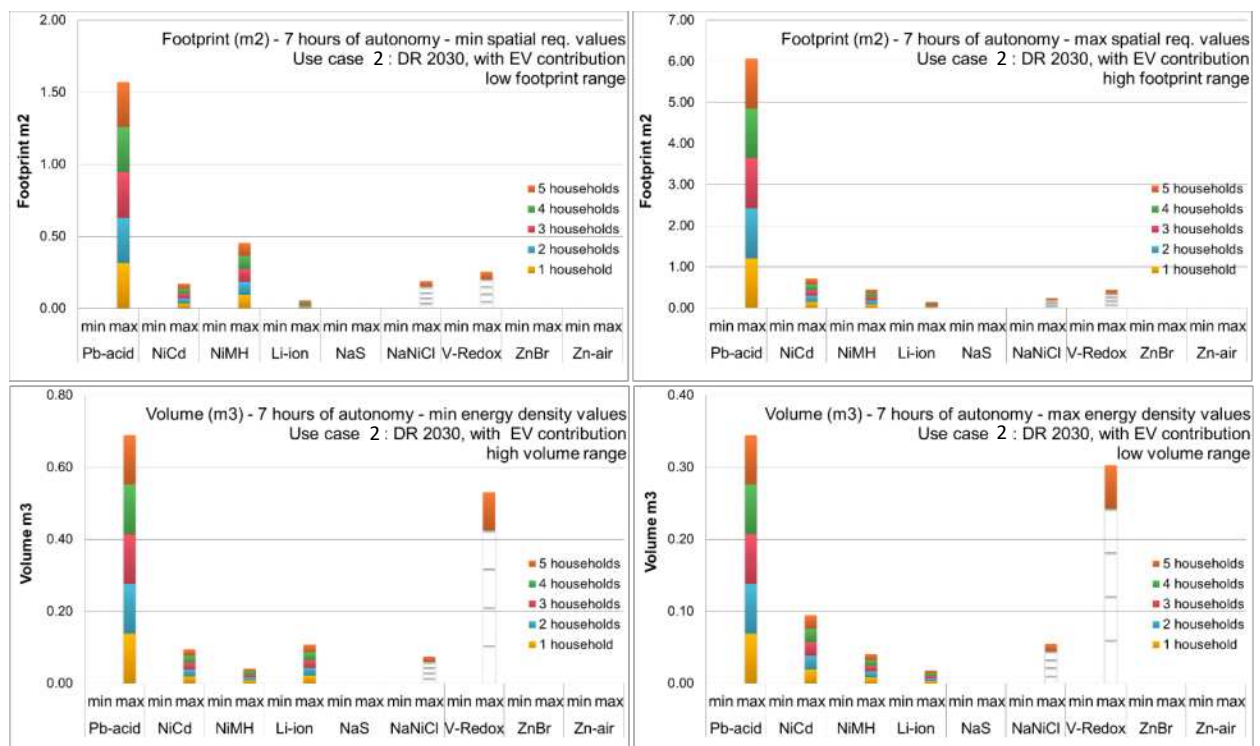
Figure 2. Nominal capacity and applicability of battery technologies for up to 5 households

In use case #5, where the charged EV feeds back to the home in the evening, in the case of low consumption households, no additional storage would be required at home level. In addition, Pb-acid could feed back an extra capacity (excluding losses) of about 65kWh, while the most efficient technologies a capacity of about 25kWh. However, not all technologies are suitable for EV applications, so NiCd, NaS, V-Redox and ZnBr would not be applicable for low consumption households.

It was observed from this exploration that the Pb-acid and Li-ion technologies already have a wide enough energy rating range to be able to serve all scales at distribution level for a sub-daily autonomy period. NaNiCl and V-Redox start being suitable in groups of buildings of 5 or more. NiCd is not available for communities of 50-75 buildings. NiMH has a more limited applicability, as it is unsuitable for communities comprising 10 to 75 households. NaS is quite unfavourable, as it cannot be applied in this use case. ZnBr and Zn-air can serve scales of at least 50 households, but ZnBr can also serve smaller scales of about 25 households.

3.2. Footprint, volume, mass, investment cost and levelised cost of energy

The graphs for footprint, volume, mass, investment cost and LCOE for communities comprising up to 5 households are presented in **Figure 3** (spanning over 2 pages) below. On the left hand side of the figure the low range of the various aspects is presented, while the high range is on the right.



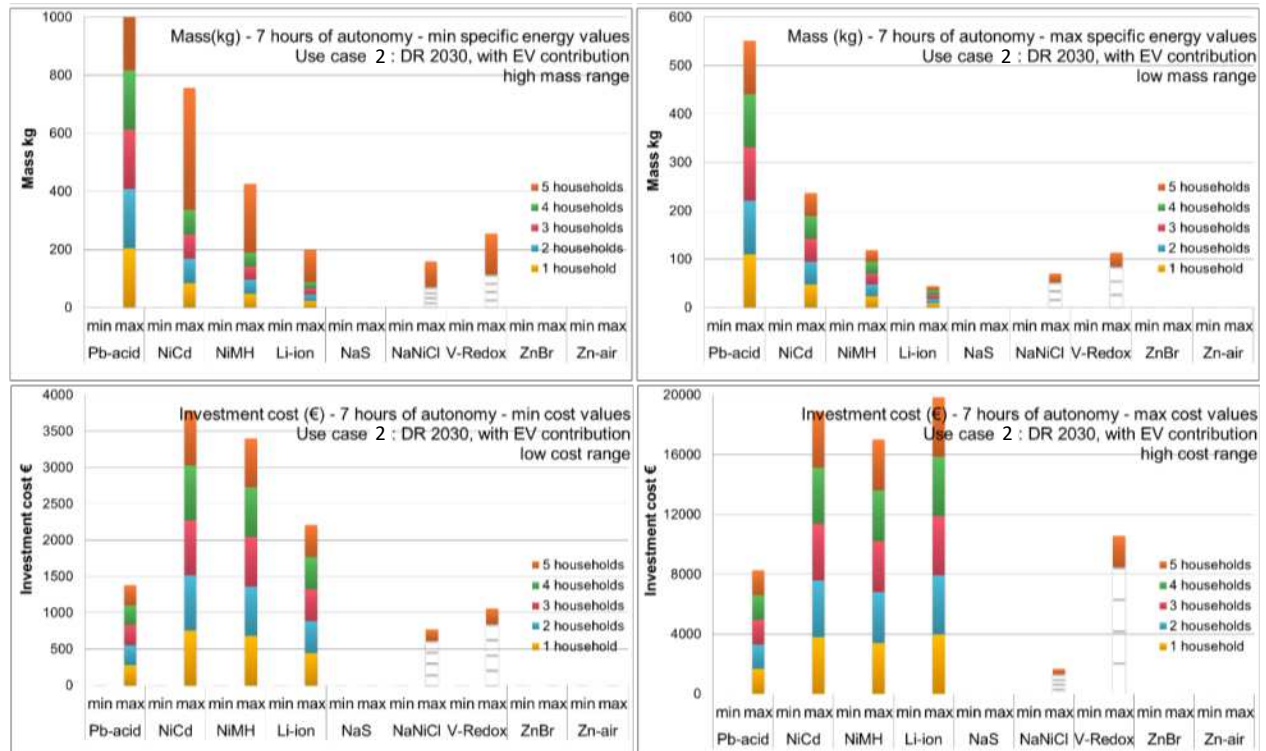


Figure 3. Comparison among footprint, volume, mass and investment cost of battery technologies

4. Discussion

The picture regarding footprint, volume, mass and investment cost is similar to the one for daily autonomy (presented in [10]), except the values and applicability in this case are lower. Pb-acid would occupy by far the most space regardless of whether the minimum or maximum spatial requirement value is considered. Li-ion and NaNiCl, where applicable, seem to be the most favourable technologies, while NiCd, NiMH and V-Redox are following closely. As an example, let's assume that the Li-ion technology was selected for storage at community level, shared among 5 households. The battery would provide 7 hours of storage supplying the electricity needed to power the appliances in the five homes from 5pm to 12am, topping up the energy supplied by the EV. Based on the exploration in this study, the Li-ion battery would then occupy an area of about 0.05m^2 - 0.15m^2 (high consumption households). In a similar example where Pb-acid technology was used, the battery would occupy an area of about 1.5m^2 - 6m^2 .

Regarding volume, Pb-acid would be the most unfavourable, requiring the highest volume regardless of whether the minimum or maximum energy density value is considered. Li-ion, NiMH and NaNiCl, where applicable, seem to be the most favourable technologies. V-Redox would require the second highest volume where applicable. Considering the previous example of Li-ion and Pb-acid in a community comprising five households, the Li-ion battery would require a volume of about 0.2m^3 - 1m^3 . If Pb-acid technology was used, the battery would need a volume of about 0.4m^3 - 0.7m^3 .

Regarding mass, Pb-acid would be the most unfavourable technology, weighing the most in all use cases regardless of whether the minimum or maximum energy density value is considered. Li-ion and NaNiCl, where applicable, seem to be the most favourable technologies. Considering the previous example, the Li-ion battery would weigh about 44kg-110kg. In a similar example where Pb-acid technology was used, the battery would weigh about 550kg-1000kg.

Regarding the investment cost, NiCd, NiMH and Li-ion would be the most unfavourable technologies, while NaNiCl, where applicable, seem to be the most favourable one. Considering the previous example, the Li-ion battery would then cost about 2,200€-20,000€. In a similar example where Pb-acid technology was used, the battery would cost about 1,400€-8,300€.

The LCOE in the four use cases is the same as for the daily storage [10] for all technologies, as the factors that would affect the LCOE values, such as cycle-life, DOD and round-trip efficiency remain the same. It is generally observed that, compared to use case 1, in use case 2 where the EV provided part of the storage for the home appliances, the footprint, volume, mass and investment costs would come down by about 90%, which signifies huge savings.

5. Conclusions

In this study a use case where the EV makes a contribution by meeting part of the storage requirement in residential buildings was investigated in terms of the architectural implications. The impact of the integration of battery technologies on the spatial requirements are minor and thus of no importance to designers. The choice of the most suitable technology according to its applicability in different building scales should be carefully assessed. In the case of low consumption households, no additional storage would be required at home level. Pb-acid and Li-ion technologies already have a wide enough energy rating range to be able to serve all scales at distribution level, while the rest of the technologies have limited applicability. It was also concluded that space and cost savings by about 90% compared to use cases with no EV contribution could be achieved, bringing significant savings.

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